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An extragalactic "flux trapping" origin of the dominant part of hadronic cosmic rays?

R.Plaga

Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany

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Abstract. An extragalactic origin of the dominant part of all extrasolar hadronic cosmic rays above about 10 MeV/nucleon has long been considered unlikely due to energy considerations. In order to circumvent such arguments, the hypothesis that "flux trapping" of extragalactic cosmic rays occurs in the Galactic confinement volume is advanced in this paper. This hypothesis is based on a number of speculative assumptions about the properties of Galactic and intergalactic magnetic fields. The intergalactic cosmic-ray density expected under conservative assumptions about its extragalactic origins is then shown to be of the right order of magnitude to account for the locally observed cosmic radiation. It is demonstrated that an extragalactic scenario of cosmic-ray origin that is consistent with the observed cosmic-ray energy spectrum and preserves the successes of Galactic propagation theory can be constructed. The position of the "ankle" in the cosmic-ray energy spectrum follows as a natural consequence from this explanation. The γ-ray flux from the Magellanic clouds is shown to provide no suitable testing ground for the decision for or against an extragalactical origin in this scenario. It is argued that recent observational evidence seems to be in favour of a dual origin of cosmic-rays. The hadronic component is mainly extragalactic while the electrons are accelerated in Galactic supernova remnants.

Key words: cosmic rays – Magnetic fields – intergalactic medium – gamma rays, observation

1. Introduction

The possibility of an extragalactic origin of the dominant part of extrasolar hadronic cosmic rays with energies above about 10 MeV/nucleon has been considered since the early days of cosmic-ray research (Baade & Zwicky 1934). In the modern era it was discussed by Burbidge(1962), Burbidge & Hoyle(1964) and later in great detail by Brecher & Burbidge(1972). Their ideas were criticized by Ginzburg(1974) and others, mainly on energetic grounds: it was argued that under reasonable assumptions the potential extragalactic sources of hadronic cosmic rays like radio galaxies, active galactic nuclei and normal galaxies are expected to fill the universe with a cosmic-ray energy density ρ_{eg} of about 10^{-4}-10^{-5} eV/cm^3 during its lifetime $t_{\mathrm{U}} \simeq 1.5 \cdot 10^{10}$ years, rather than the locally observed value $\rho_{\mathrm{loc}} \simeq 0.5$ eV/cm^3. Section 3 presents a hypothetical explanation for the local cosmic-ray density which avoids the above conclusion by way of a "density enhancement" in the Galaxy. The present knowledge about intergalactic cosmic-rays is discussed in connection with this explanation in Sect.4. Sect. 5 contains a speculative scenario for the origin of the observed cosmic-ray energy spectrum.

There is now impressive experimental evidence for an origin of the electron part of the cosmic rays in Galactic supernova remnants (SNRs) (see Sect.4). On the other hand no direct, incontrovertible evidence for any Galactic source of hadronic cosmic rays has been found up to now. An extragalactic origin for hadronic cosmic rays below about 10^{18} eV has therefore generally been considered unlikely but not impossible(Longair 1994). After a discussion of the observational evidence in Sect.6, I will argue in the conclusion that an extragalactic origin of the hadronic and a Galactic origin of the electron component could be the most natural explanation of the observational facts. A few years ago Sreekumar et al.(1993) interpreted their upper limit on γ-radiation with energies above 100 MeV from the Small Magellanic cloud (SMC) obtained by the EGRET detector as excluding an extragalactic origin of cosmic rays. Section 7 examines this conclusion in the light of ideas of this paper.

Recently very intense VHE γ radiation (energy range 0.3 -10 TeV) of extragalactic origin was observed by several groups (see e.g. Deckers et al. 1997). These observations may well turn out to be the first direct experimental evidence for an acceleration site of hadronic cosmic rays ("the proton blazar", see Mannheim et al. (1996)). It was this unexpected discovery that prompted the present author

Send offprint requests to: plaga@hegra1.mppmu.mpg.de

to reconsider the “extragalactic option” for the origin of the main part of hadronic cosmic rays.

2. Necessary conditions for an extragalactic origin of cosmic rays and intergalactic diffusion

Before I discuss the specific assumptions for the hypothesis of this paper I list the basic conditions which have to be fulfilled for an extragalactic origin of cosmic rays. Low energy cosmic rays can reach earth from intergalactic space if the following conditions are fulfilled:

- a hypothetical Galactic wind streams outwards from the Galactic centre with a velocity below about 30 km/sec so that cosmic-ray transport is dominated by diffusion rather than by convection. This may well be true because it is uncertain if a universal Galactic wind exists at all (Berezinskii et al. 1990). There is some evidence that our Galactic disk may have “chimneys” (Norman & Ikeuchi 1989) where interstellar matter is rapidly streaming out, but *most* of the disk's volume may satisfy the mentioned limit on velocity.
- the field lines of the galactic-halo magnetic field are not entirely closed, therefore cosmic-ray particles of all energies can enter the Galaxy. This point is discussed in detail in the next section.
- the diffusion coeffcient D_{IG}, which describes the intergalactic propagation of cosmic rays near our Galaxy (i.e. outside dense galaxy clusters and galaxy poor “cosmological voids”) has to be large enough to allow the diffusion of cosmic-ray particles from extragalactic cosmic-ray sources located at a distance d from our Galaxy within the lifetime of the universe t_U:

$$D_{IG} > \frac{(d/4Mpc)^2}{(t_U/1.5 \cdot 10^{10} years)} \simeq 3 \cdot 10^{32} cm^2 sec^{-1} \qquad (1)$$

Here 4 Mpc is the distance to Cen A, a nearby very extended radio galaxy which had been identified by Burbidge(1962) as a likely source of extragalactic cosmic rays. The actual value of D_{IG} is unknown presently. Ginzburg & Syrovatzkii (1964) give limits[1] on D_{IG} of 10^{31} cm^2 sec^{-1} < D_{IG} < 10^{35} cm^2 sec^{-1}.

The strength of the intergalactic magnetic field B_{IGM} near our Galaxy is unknown. It could be extremely low (below 10^{-18} G) if galactic winds and jets from active objects did not manage to fill the universe with magnetized plasma (Kronberg 1994). Otherwise a mean value very roughly around 10^{-11} G has been estimated by Daly & Loeb (1990). I estimated a modern estimate for D_{IG} by scaling the most likely value of the intracluster diffusion coefficient D_{IC} in the Coma cluster as derived by Schlickeiser et al.(1987) ($D_{IC} \simeq 10^{29}$ cm^2 sec^{-1}) for an assumed intracluster magnetic field of $3 \cdot 10^{-6}$ G, to an intergalactic field with field strength of 10^{-11} G. For this I used the assumption, made recently by Völk et al.(1996), that D $\sim$ $E^{0.5}$ in the intergalactic medium. One derives an estimate of $D_{IG} \simeq 10^{32}$ cm^2 sec^{-1}. If intergalactic fields are weaker the number could be higher.

In summary it seems quite likely that inequality (1) is in fact fulfilled but possibly not by a large margin.

3. Magnetic flux trapping in the Galaxy

In this Sect. the central hypothesis of this paper that extragalactic cosmic rays are “concentrated” in the Galaxy is discussed. Parker (1965) has long argued that the magnetic field lines of the Galaxy are generally closed. Due to the dynamical pressure of confined cosmic radiation, instabilities form along the field lines, and the magnetic field together with relativistic plasma is expelled out of the Galactic confinement volume. These loops are assumed to be the places where cosmic rays escape from the Galaxy (Jokipii & Parker 1969). Let us assume that in a fraction of cases some dissipational mechanism exists and the magnetic field of these “Parker loops” reconnects with the ambient intergalactic field (Parker 1992). In this case the intergalactic cosmic rays on the connected field lines could enter the Galaxy(fig.1). A “reconnection factor” f_r can be defined as:

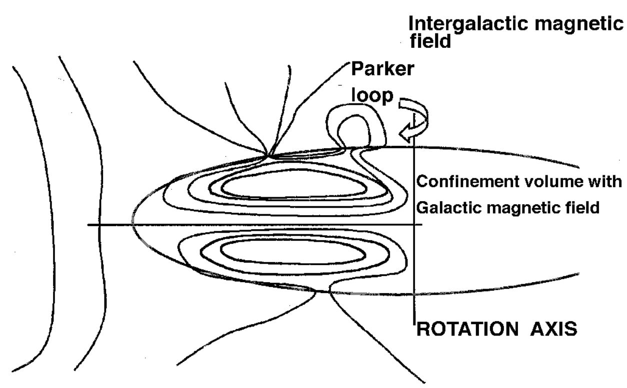

Fig. 1. Schematic sketch of the hypothetical general topology of the Galactic and intergalactic magnetic field assumed for the present scenario. The field is generally closed, but some Parker loops connect to the intergalactic magnetic field. Cosmic rays enter through the connected loops and escape through all loops.

$$f_r = A_f/A_g \qquad (2)$$

where A_f is the area in intergalactic space far away from the Galaxy perpendicular to the field direction from which field lines connect to the Galaxy, and A_g is the geometrical area of the Galactic disk.

The assumptions for the hypothesis of “flux trapping” advanced in this paper can be summarized as:

1. $f_r \simeq 1$ with a predominantly but not completely closed

[1] I converted these limits to an intergalactic matter density of $10^{-6}/cm^3$ instead of $10^{-5}/cm^3$ as assumed by Ginzburg & Syrovatzkii. Even lower numbers would raise the lower limit.

Galactic magnetic field geometry. [2]
2. A relatively small intergalactic field strength ($B_{\rm IGM} <$ 10^{-10} G, see below).
3. Conservation of the "adiabatic invariant" $\sin^2(\theta)/B_{\rm IGM}$ (Ginzburg & Syrovatskii 1964) in intergalactic propagation of cosmic rays. Here θ is the pitch angle. This amounts to the assumptions that distances with variations in the intergalactic field are generally large with respect to distances associated with particle motions. Taking into account that e.g. for an energy of 1 GeV and $B_{\rm IGM} \simeq 10^{-11}$ G the gyro-radius is about 1 light year the assumption seems reasonable. It is however the most controversial of all listed assumptions.
4. Origin of extragalactic cosmic rays in regions with a magnetic field strength $B_{\rm er}$ comparable or larger than the Galactic field strength $B_{\rm Gal}$ and a metallicity not very different from the Galactical one. The former assumption is quite plausible because galaxies, active objects and galaxy clusters are known to possess such field strengths (Kronberg 1994). The equilibrium field strengths in the lobes of radio galaxies also usually fulfill this condition (Ginzburg & Syrovatskii 1964). The latter assumption can be fulfilled under various circumstances (see sect. 4).

If cosmic rays escape from a high field region (assumption 4) into a low field region conserving the adiabatic invariant (assumption 3) they have small pitch angles below a maximal angle $\theta_{\rm max} = \arcsin(\sqrt{B_{\rm IGM}/B_{\rm er}})$ (Ginzburg & Syrovatskii 1964). Under these conditions the particles can freely enter the Galactic confinement volume via the open field lines.

Because of various inhomogeneities of the Galactic magnetic field down to very small scales, the adiabatic invariant is generally assumed *not* to be conserved during Galactic propagation (Cesarsky 1980): The cosmic rays are expected to fill all Galactic field lines during their propagation by spreading to other field lines due to the irregular component of the Galactic magnetic field(Ptuskin 1979). All of momentum space is filled due to pitch-angle scattering, e.g. by hydromagnetic waves.

Even with $f_{\rm r} \simeq 1$ (assumption 1 above) there could be Parker loops which do not connect to intergalactic field lines. Let us first consider the limiting case in which *all* Parker loops are fully connected, however. Liouville's theorem would then predict a cosmic-ray density enhanced by $b_{\rm conc,equ}$ relative to the intergalactic value throughout the Galaxy with the same energy spectrum as in intergalactic space. This is because according to Liouville's theorem the directional differential intensity along a field line has to be constant, while the radiation is constrained to move with small pitch angles outside but not inside the Galaxy due to the conservation of the adiabatic invariant. Both conditions together can only be fulfilled with an enhanced total density of cosmic radiation inside relative to the outside of the Galaxy. The flux in the weaker field is reduced in proportion to the permitted cone. This solid angle "enhancement" factor is given for the case of $B_{\rm Gal}/B_{\rm IGM} \ll 1$ (Ginzburg & Syrovatskii 1964):

$$b_{\rm conc,equ} = 2B_{\rm Gal}/B_{\rm IGM} \tag{3}$$

For an assumed intergalactic field strength of 10^{-11} G and a typical Galactic field strength $B_{\rm Gal}$ of a few μG, a density enhancement of more than a factor 10^5 would be expected[3].

In reality, the above conclusion of a concentration factor of $b_{\rm conc,equ}$ is probably too extreme. Once the cosmic-ray energy density rises above the energy density of the Galactic magnetic field, additional Parker loops are expected to form. These do not connect to intergalactic field lines, and there cosmic rays could leave the Galaxy e.g. via loops "detached" from the Galactic magnetic field (Parker 1992). The mean lifetime of cosmic rays in the Galaxy would drop, until an equilibrium between the incoming extragalactic cosmic rays and the total loss of cosmic rays from the Galaxy, at a total pressure similar to the Galactic magnetic-field energy density, is reached. Let us assume that cosmic rays mainly escape via Parker loops through which they do not enter. This will be the case if the cosmic-ray equilibrium density, equal to the local density at earth $\rho_{\rm loc}$ [4], is much smaller than the product of extragalactical cosmic-ray density $\rho_{\rm eg}$ and the concentration factor $b_{\rm conc,eq}$. This condition corresponds to intergalactic field strengths below about 10^{-10} G according to Eq.(3) together with the cosmic-ray energy densities quoted in the introduction. The local density of cosmic rays $\rho_{\rm loc}$ will then be determined by the total influx of extragalactic cosmic rays (parametrized by $f_{\rm r}$ and the extragalactic density $\rho_{\rm eg}$) and the confinement time $t_{\rm conf}$ of cosmic rays in the Galaxy. This density will be enhanced over the intergalactic value by a factor e which is given as:

$$e \equiv \rho_{\rm loc}/\rho_{\rm eg} = f_{\rm r}\frac{t_{\rm conf}}{t_{\rm equiv}} \tag{4}$$

Here $t_{\rm conf}$ is the lifetime of cosmic-ray in the Galactic disk and halo (the confinement volume) due to magnetic diffusion generated trapping. $t_{\rm equiv}$ is the lifetime of cosmic-ray particles in an equivalent volume of intergalactic space. Equation (4) is valid only if the cosmic rays mainly escapes through pathways through which it does not enter, as in the above scenario. More generally, only an inequality $e \leq f_{\rm r}\,\frac{t_{\rm conf}}{t_{\rm equiv}}$ is valid. In this situation Galactic propagation is expected to be very similar to the one in present models

[2] A completely open field geometry, as would be expected from a primordial origin of the Galactic magnetic field, is improbable for reasons which have been discussed in connection with an extragalactical origin of cosmic rays by Parker (1973).

[3] This concentration mechanism was already briefly mentioned by Burbidge(1962) and is discussed in greater detail in a context related to the present one by Sciama(1962).

[4] The local density is taken to be representative for the one in the Galactic confinement volume in general, in this paper.

which have considerable experimental support (Ferrando 1994). Only the “source” of hadronic cosmic rays is not some Galactic object class, but the influx of extragalactic cosmic rays.

Let us estimate the enhancement e expected from the parameters of Galactic cosmic-ray propagation theory, which are based on experimental data. The lifetime of particles in the Galactic confinement volume is given as:

$$t_{\rm conf} = \frac{d^2}{D_{\rm G}} \tag{5}$$

where d is smallest extension of the confinement volume (the thickness of the disk if it is assumed to have a cylindrical shape) and $D_{\rm G}$ is the Galactic diffusion coefficient. I will assume parameter values[5] derived in a diffusion model based on experimental data with ^{10}Be at an energy per nucleus of 3 GeV (Ferrando 1994): d $\simeq$ 3 kpc, $D_{\rm G} \simeq 10^{28}$ cm^2 sec^{-1} and consequently $t_{\rm conf} \simeq 3 \cdot 10^8$ years. The lifetime $t_{\rm equiv}$ of a particle in an equivalent volume in intergalactic space, is given by:

$$t_{\rm equiv} = \frac{d^2}{D_{\rm IG}} \qquad for\, D_{\rm IG}/d < c \tag{6}$$

$$t_{\rm equiv} = \frac{d}{c} \qquad for\, D_{\rm IG}/d > c \tag{7}$$

Assuming that Eq.(1) holds, Eq.(7) has to be used for the calculation of $t_{\rm equiv}$ and I finally obtain (with $f_{\rm r}$ =1) :

$$e = \frac{dc}{D_{\rm G}} \simeq 3 \cdot 10^4 \tag{8}$$

One can compare this with the energy density of intergalactic cosmic rays of 10^{-4}-10^{-5} eV /cm^3 estimated by critics of the extragalactic hypthesis of cosmic-ray origin, quoted in the introduction: Remarkably one gets as a natural and “untuned” consequence of our scenario:

$\rho_{\rm loc} \simeq \rho_{\rm eg} \cdot e$

The predicted enhancement factor e has the right order of magnitude to explain the local energy density of cosmic rays, under the assumption of an extragalactical cosmic-ray energy density which is considered likely by most workers in the field.

The above “flux trapping” hypothesis has a certain similarity to the particle trapping in the van Allen radiation belts around earth, where the low energy cosmic-ray density is concentrated by a factor of about 10^4 relative to the interplanetary value due to the action of a relatively strong magnetic fields on cosmic rays(Hess 1968). In both cases the general conditions and physical mechanisms are different, however[6].

4. On the density and origin of intergalactic cosmic rays

Under which circumstances do intergalactic cosmic rays have the right density to account for the local hadronic cosmic rays under the assumptions of the previous section, and what is their origin? The expected energy density of extragalactic cosmic rays $\rho_{\rm eg}$ relative to the locally observed $\rho_{\rm loc}$ one, can be roughly estimated to be:

$$\begin{aligned}\rho_{\rm eg}/\rho_{\rm loc} \;=\; & 10^{-4} \times \left(\tfrac{\Omega_{\rm B}}{0.01}\right) \times \left(\tfrac{\rho_{\rm c}}{10^{-29} g}\right) \times \left(\tfrac{M_{\rm g}}{2\cdot 10^{44} g}\right) \times \\ & \left(\tfrac{\epsilon}{3\cdot 10^{40} erg/sec}\right) \times \left(\tfrac{\rho_{\rm BP}/\rho_{\rm N}}{10}\right) \times \\ & \left(\tfrac{\rho_{\rm AGN}/\rho_{\rm N}}{1}\right) \times \left(\tfrac{\epsilon_{\rm h}/\epsilon_{\rm e}}{100}\right) \times \left(\tfrac{V_{\rm U}/V_{\rm conf}}{1}\right)\end{aligned} \tag{9}$$

The symbols are defined as:

$\Omega_{\rm B}$ baryonic mass fraction relative to critical density $\rho_{\rm c}$

$\rho_{\rm c}$ is the cosmological critical mass density

$M_{\rm g}$ is the mass of a galaxy similar to the Milky Way

ϵ is the cosmic-ray production rate of such a galaxy

$\rho_{\rm BP}$,$\rho_{\rm N}$ are the total amount of cosmic rays produced by such a galaxy during its early bright starburst phase and later normal life respectively(Völk et al. 1996)

$\rho_{\rm AGN}/\rho_{\rm N}$ is the total amounts of cosmic rays produced by active objects (radio galaxies, active nuclei, quasars etc.) relative to the amount produced by normal galaxies. The values for both this and the previous parameter are extremely uncertain and could be very different from the ones chosen in Eq.(9) (see discussion at the end of this section.)

$\epsilon_{\rm h}/\epsilon_{\rm e}$ is the relative efficiency of hadron and electron acceleration

$V_{\rm conf}, V_{\rm U}$ is the intergalactic confinement volume (e.g. the volume of all superclusters, see below) for hadronic cosmic rays and the volume of the universe respectively

The numbers displayed are standard choices, and lead to a value of $\rho_{\rm eg}$ with an order of magnitude required for an extragalactic origin in the scenario discussed in Sect.3. There is an alternative non-standard possibility to choose the parameter values, which leads to the same density $\rho_{\rm eg}$ and is more likely in my opinion. It is well known that electrons cannot be of extragalactic origin because at energies above about 1 GeV they loose energy by Compton scattering too quickly to travel extragalactic distances (Longair

[5] These values were derived under the assumption that cosmic rays are produced in the Galaxy. They remain approximately valid for our case if the mass density crossed by the particles prior to the entry is negligible. Intergalactic propagation during $t_{\rm U}$ would only contribute about 10^{-4} to the total grammage crossed by cosmic-ray particles. In using these values I assume that the propagation in the extragalactic acceleration site is negligible compared to the later Galactic one (see discussion in Sects. 4 and 6).

[6] Another analogous situation is the flux trapping in high-flux nuclear fission reactors. The neutron density is increased in the moderator because neutrons crossing the moderation zone have a larger lifetime due to a smaller capture cross section in ^{238}U(Byrne 1994). Cosmic rays crossing the Galactic confinement volume have a larger lifetime than in an “equivalent volume” of intergalactic space because of a lower “effective speed” due to the action of diffusion.

1994). Moreover there is recent experimental evidence for a supernova-remnant (SNR) origin of Galactic cosmic-ray electrons (Koyama et al. 1995; Mastichiadis & de Jager 1996). However, if the locally observed cosmic-ray electrons are produced by SNRs and $\epsilon_{\rm h}/\epsilon_{\rm e}$=100, Galactic and intergalactic hadronic cosmic rays would have comparable intensities. I will argue in Sect.6 that some observational facts are explained in the most natural way if hadronic cosmic rays have a *mainly* extragalactical origin. A plausible parameter choice in Eq.(9) is therefore that $\epsilon_{\rm h}/\epsilon_{\rm e}$ is roughly on the order of 1 [7] and e.g. $V_{\rm U}/V_{\rm conf}$, $\rho_{\rm BP}/\rho_{\rm N}$ and $\rho_{\rm AGN}/\rho_{\rm N}$ are larger than the values chosen in Eq.(9) to give a comparable total cosmic-ray energy density. With this alternative choice of parameter values Galactic SNRs would contribute only a small fraction to the locally observed hadronic cosmic rays. Such a situation would be in good accord with the observational data discussed in Sect.6. A value larger than 1 for $V_{\rm U}/V_{\rm conf}$ is plausible because $\rm D_{IG}$ is possibly not large enough to allow a filling of the cosmological "voids" in the matter distribution (see the discussion in Sect.2). The effective confinement volume for the bulk of cosmic radiation below a certain energy would then be the Galaxy rich "walls", of which the local supergalaxy is a part. The confinement volume of intergalactic cosmic rays was estimated to fill a fraction of about one percent of the total volume of the universe by Brecher & Burbidge (1972). A modern rough estimate for volume of the walls is about 20 to 40 % of the total volume of the universe (assuming a thickness of 6/h Mpc for the sheets, and a size of 50 - 100 Mpc/h for the voids, where h is the Hubble constant in units of 100 km/sec/Mpc (Peebles 1993)).

It is presently a completely open question if the intergalactic hadronic cosmic-ray density was mainly produced in normal galaxies or active objects. If the latter dominates, radio galaxies like Cen A seem to be the most natural accelerators for the locally observed hadronic cosmic rays in the present scenario. The low ambient matter density in their giant radio lobes probably allows the acceleration of heavy elements with negligible spallation processing. The acceleration of extragalactic cosmic rays in radio galaxies has been discussed in detail by Rachen & Biermann (1993) in the context of cosmic rays with very high energies above 10^{18} eV[8]. Another plausible option is that the intergalactic cosmic-ray energy density is mainly supplied by galaxies with a very high rate of star formation, like galaxies in a starburst phase. They develop strong galactic winds which lead to termination shocks at which efficient particle acceleration can occur (Völk et al. 1996). In this case hadronic cosmic rays would be mainly produced in *extragalactic* termination shocks.

5. Speculative extragalactic scenario for an explanation of the cosmic-ray energy spectrum

In this section I demonstrate that the "enhancement mechanism" of section3 together with standard ideas about Galactic propagation of cosmic rays is consistent with the observed energy spectrum of cosmic rays. The purpose of the proposed scenario is only to demonstrate that a consistent explanation does not seem to meet unsurmountable difficulties. It is virtually certain that the whole truth is much more complicated than the simple picture outlined below. First I assume that the "knee" feature, where the observed all-particle cosmic-ray spectrum (Berezinskii et al. 1990) steepens from a power law with a differential index of α=-2.6 to α=-3.0 at an energy of 2 PeV is already present in the local intergalactic spectrum. This intergalactic spectrum is assumed to steepen from α=-2.1 below the knee to α=-2.5 above. If hadronic cosmic rays are confined to certain regions of the universe like the local supergalaxy (see previous section), the "knee" could mark the energy where the cosmic rays are no longer completely confined and begin to leak out into the cosmological voids. In this case cosmic rays of very high energy would be much younger than the age of the universe $\rm t_U$. I will further assume the following dependence of the Galactic diffusion coefficient $\rm D_G$ on the cosmic-ray energy E:

$$D \sim E^a \tag{10}$$

with a =0.5. This value for a is in agreement with experimental observations and theoretically plausible (Ferrando 1994). According to Eq.(4) and Eq.(10) I get:

$$e = 3 \cdot 10^4 (E/3GeV)^{-0.5} \tag{11}$$

[7] Donahue (1951) has argued for such a choice as the most natural one in the Fermi acceleration mechanism. He then concluded from the small observed cosmic-ray intensity of electrons relative to hadrons, that a large part of primary electrons had to be lost during propagation due to inverse Compton scattering on photons. This excluded a Galactic origin due to a resulting too small photon surface density. Donahue identified a local solar (with high photon densities) and an extragalactical origin (with large pathlengths) as the remaining possibilites. Although the microwave background radiation was not known when Donahue wrote his paper, his conclusion remains valid when making his assumption about acceleration efficiency of hadrons.

[8] Rachen & Biermann (1993) assume that mainly protons are accelerated in this environment. Whether or not this assumption is true, depends on the question whether the intergalactic medium in the surroundings of the radio galaxy is primordial or consists of chemically processed plasma from an early generation of active objects. As discussed in Sect.2, it is presently not clear which option is correct. Especially in the local supergalaxy the second option might be closer to reality. Nath & Trentham (1997) recently argued that the intergalactic medium was enriched with heavy elements already at very early times. Another possibility for extragalactical acceleration with non-primordial abundances is an acceleration site in the inner (but nonnuclear) region of active objects (Norman et al. 1996). It is therefore quite possible that condition 4. in Sect.3 is fulfilled.

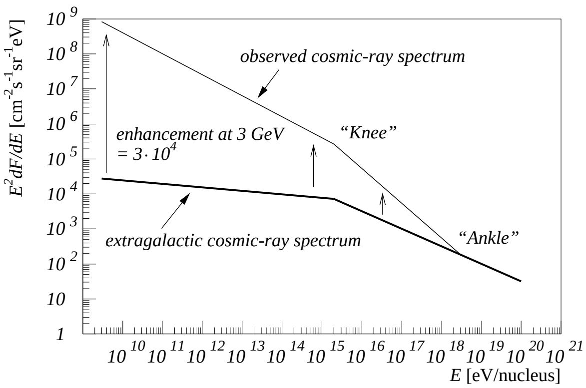

Fig. 2. An extragalactical scenario for the origin of the observed cosmic-ray spectrum near earth. Plotted is the differential flux of hadronic cosmic rays multiplied by E^2 as a function of the cosmic-ray energy per nucleus E . The thin line is a schematic representation of experimental results. They are explained by an extragalactical spectrum outside the Galaxy (thick line) which is enhanced in the Galaxy by a factor e (symbolized by the arrows). This factor varies $\sim E^{-0.5}$. Only at energies above the "ankle" the extragalactical spectrum is equal to the observed spectrum.

This leads to an expected local spectrum in agreement with observations (fig.1). e=1 (i.e. no more "flux trapping" enhancement over the intergalactic density) is therefore expected at an energy of

$E_{e=1}$= 3 GeV $\cdot\, e^{1/a} \simeq 3 \cdot 10^{18}$ eV

This is about the energy where the power-law index of the observed cosmic-ray spectrum is observed to change from -3.0 to -2.6 at higher energies ("ankle"). Detailed studies show that the observed spectrum is described by a superposition of a steep component at low energies and component with α=-2.5 at higher energies (Sokolsky 1994). An extragalactical origin of cosmic rays above the "ankle" has long been considered likely. The power law index and intensity of this component follow quantitatively as a natural consequence of our scenario.

6. Observational arguments in favour of an extragalactic origin

After refuting an often made counter argument for an extragalactical origin of the heavy elements in the cosmic rays, I discuss two recent pieces of experimental evidence which could point towards a non Galactic origin of hadronic cosmic rays.

Longair (Longair 1994) quotes as evidence *against* an extragalactic origin of cosmic rays the fact that cosmic-ray clocks like ^{10}Be indicate an "age" of cosmic rays of a few tens of million years (Ferrando 1994). This is much less than the expected time since acceleration in an extragalactic scenario, which is on the order of the age of the universe t_U. What cosmic rays clocks measure, however, is the time since they have been propagating in a medium dense enough to lead to nonnegligible spallation processing (the radioactive ^{10}Be is a spallation product from nuclear reactions during propagation and not a remnant from the acceleration site). If extragalactic cosmic rays were accelerated in regions with low matter density and then propagated in the intergalactic medium which has a very low ambient density, the measured "age" merely measures the time since entering the Galaxy, which is on the order of t_{conf}, like in the Galactic scenario of cosmic-ray origin.

The first argument concerns the high-energy γ-ray emission from Galactic SNRs. If hadronic cosmic rays are of Galactic origin, only SNRs seem to able to accelerate enough particles to replenish the cosmic rays lost to intergalactic space (Biermann 1994). While the properties of the observed hadronic cosmic rays and the ones theoretically expected from SNRs under simple assumptions are not in perfect agreement[9], a first order Fermi acceleration of particles in these objects seems eminently plausible(Berezhko & Völk 1997).

The mean energy put into the production of hadronic cosmic rays for a typical SNR is constrained to be on the order of 10^{50} erg by the requirement to supply the local cosmic radiation. VHE and UHE γ-ray emission from these objects is then expected due to π_0 production in cosmic-ray interactions with ambient matter (e.g. molecular clouds) and has been quantitatively calculated in several seminal papers by a Heidelberg/Dublin group (e.g. Aharonian et al. (1994)) and others (Baring et al. 1997). The predicted levels are on the order of the sensitivities of various ground based γ-ray detectors. The nondetection of VHE and UHE γ-radiation from shell type SNRs (Hess 1997; Lessard et al. 1997; Prosch et al.1996) is therefore becoming problematic for the Galactic senario. Similar detailed work (identification of plausible sources for the locally observed hadronic cosmic rays, calculation of predicted γ-intensities followed by observations) under the assumption of an extragalactic scenario for cosmic-ray origin is urgently needed.

A second completely idenpendent argument concerns the distribution of hadronic cosmic rays as a function of galactocentric radius. Recent measurements by the EGRET experiment confirmed the earlier conclusion drawn from data taken with the COS-B satellite that the galactocentric falling gradient of the cosmic ray density is much smaller than expected for any plausible class of Galactic cosmic-ray sources (Erlykin et al. 1996). The only natural possibility to explain this within the Galactic scenario (where the production of the major part of cosmic rays is expected to take place within the solar circle) seems to be to assume a confinement volume in an extended halo

9 E.g. Drury (1995) noted that the absence of any feature in the observed hadronic cosmic-ray spectrum around the expected theoretical upper cut-off energy (about 100 TeV under the simplest assumptions) is unexpected if the observed hadronic cosmic-rays have a SNR origin.

of the Galaxy (extension from the Galactic center with a length scale of $r_e > 15$ kpc)(Berezinskii et al. 1990) in which the cosmic-ray density would be roughly constant. This in turn would lead to the expectation of a cosmic-ray anisotropy in the direction towards the antigalactic center due to the Compton-Getting effect which can be roughly estimated as:

$$\begin{aligned} \delta &\simeq (\alpha+2)(v_{\rm out}/c) \simeq (\alpha+2)D_{\rm G}/r_{\rm e}c \\ &\simeq 0.1(E/100TeV)^{0.5} \end{aligned} \tag{12}$$

Here α is the differential power-law index of the cosmic-ray energy spectrum, and v_{out} the effective streaming velocity away from the central region of the Galaxy. The energy dependence of D_G from Eq.(10) was assumed. Moreover I set $D_G \simeq 2 \cdot 10^{29}$ cm^2 sec^{-1}, in order to reproduce the empirical storage times of smaller than a few 10^8 years together with the existence of an extended halo. The predicted value lies more than two orders of magnitude above the observed value of $\delta \simeq 8 \cdot 10^{-4}$ (Munakata et al. 1997) around 100 TeV primary energy. Though it might be possible to find a model with very different diffusion coefficients in the disk and halo and/or cosmic-ray transport via Galactic winds (Erlykin et al. 1997) which explains the observations within the Galactic scenario, the magnitude of the discrepancy seems severe.

In the extragalactic picture the Compton-Getting effects from Galactic rotation and proper motion of the Galaxy are suppressed by a factor e (Eq.(4)) (Brecher & Burbidge 1972) and therefore to small to be presently observable. To zeroth order no galactocentric gradient at all is expected in the extragalactic scenario. The small observed gradient (Erlykin 1996) can be explained as due to a contribution by Bremsstrahlung from electrons which are presumably of Galactic origin (see next section) and therefore do show a gradient. A small gradient of the hadronic cosmic rays could be due to a slight decrease of e with galactic radius. This might be expected if the Galactic confinement volume is not exactly spherical or cylindrical but shaped like a thick disk decreasing in thickness with galactocentric radius.

7. The non-detection of the SMC in the light of γ-rays

Sreekumar et al.(1993) have argued that their non-detection of γ-radiation above 100 MeV from the Small Magellanic cloud (SMC) rules out an extragalactic origin of cosmic-rays. Taking into account magnetic-flux trapping it is clear that the density of cosmic rays in the SMC is not simply expected to be equal to the local one near earth, as assumed by Sreekumar at al.. Rather it is given by the local density times a factor $e_{\rm SMC}/e$. Here $e_{\rm SMC}$ is the enhancement factor valid for the SMC analogous to e (Eq.(4)) for the Galaxy. $e_{\rm SMC}$ is probably smaller than e because the corresponding t_{conf}(SMC) is smaller than the Galactic value due to the smaller size and possibly dynamical disintegrating state of the SMC. A smaller t_{conf}(SMC) is also directly responsible for the low γ-ray luminosity of the SMC in the Galactic scenario for cosmic-ray origin. It is thus clear that the γ-ray luminosity of the SMC is no suitable testing ground for a decision in the question of Galactic versus extragalactic origin of cosmic rays.

8. Conclusion

The assumptions made for the basic hypothesis of flux trapping (listed in Sect.3) are speculative and controversial. A better understanding of very complex magnetohydrodynamic processes in intergalactic space is needed to make a firm decision whether they are realistic or not. Unfortunately all present theories of cosmic-ray origin need to assume some unproven facts. From a purely phenomenological point of view the following point of view seems interesting:

Galactic SNRs produce the observed electron cosmic-ray flux. The required acceleration efficiency is modest and the high-energy cutoff lies in the region of 10 TeV, in good agreement with theoretical expectation (Mastichiades & de Jager 1996). Protons and nuclei are perhaps accelerated with a roughly similar efficiency (i.e. much less than with a 100 times higher efficiency as required in a scenario with Galactic origin) and high-energy cutoff (see Sect.4), and therefore produce a local hadronic cosmic-ray intensity similar to the electron intensity (about 1 % of the total intensity below the cutoff). The main part of hadronic cosmic rays is due to intergalactic cosmic radiation which has an enhanced density in the Galactic confinement volume [10].

In the scenario of Sect.5 cosmic rays with extremely high energies have the same origin as the bulk of hadronic cosmic rays. This gives added importance to an experiment like Auger (Mantsch 1996), which tries to find the site of origin of cosmic rays with the highest energies. Experiments searching for antimatter in cosmic-rays of extragalactic origin like AMS (Ahlen et al. 1994) would have a sensitivity orders of magnitude higher than previously thought.

[10] The present situation in the question of hadronic cosmic-ray origin (HCR) has some parallels to the situation in the question of the nature of γ-ray bursts (GRB) until very recently (Paczynski 1995): After a long period (HCR: 30 years, GRBs: 15 years) in which a Galactic origin was accepted nearly unanimously in the community, new data (HCR: weak Galactocentric gradient in combination with high degree of isotropy, absence of VHE/UHE γ-rays from SNRs; GRB:number-luminosity relationship in combination with high degree of isotropy, time-dilation effects in bursts) and a growing appreciation for the possibility of certain physical processes (HCR: magnetic-flux trapping, GRB: formation of relativistic fireballs) forces us to take the "extragalactic alternative" serious. In both cases only a localization in a very extended Galactic halo remains a possibility in an "undecided" period, where both models are taken serious.

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